The Reliability Research of DF-D2D Underlaying Cellular Networks

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***Abstract*—In this paper, we propose a novel Device-to-Device (D2D) communication model, i.e., DF-D2D where the D2D communication is aided by a relay using the decode-and-forward (DF) strategy. Based on this model, we firstly analyze the outage probability and thereby obtain its exact expression. Then, we compare this probability with that of D2D. Finally, we obtain a threshold in which the reliability of DF-D2D is better than that of D2D based on the distances between different DF-D2D users. Analysis and simulation results show that DF-D2D could dramatically improve the reliability of conventional D2D systems when the location of the relay user changes within the threshold.**

***Index Terms*—cellular networks, D2D communication, DF strategy, DF-D2D communication, outage probability.**

I. INTRODUCTION

With the rapid development of mobile communication, the demands of higher data rates for local area services are increased, which lead to a spectrum scarcity in cellular networks (CNs). Device-to-Device (D2D) communication as an underlay coexistence with CNs could effectively solve this trouble, as it is able to improve the spectrum utilization percentage by the spectrum sharing method [1-4]. Moreover, D2D can enhance cell throughput, reduce the power of users and increase the instantaneous data transmission rate [5-9]. By virtue of above advantages, D2D is becoming a hot research topic.

At the early age of 3GPP [10], D2D has been researched, and recently, 3GPP LTE-Advanced is planning to use D2D as one method to improve the overall performance of CNs. For this purpose, one of important issues in D2D communication underlaying CNs is setting up reliable links between D2D users, so as to guarantee the reliability of D2D systems.

Toward this end, several approaches have been proposed to improve the reliability of D2D systems from the aspect of interference suppression mechanisms [11-13]. Doppler proposed a D2D transmitter power control method [11]. This method can reduce the D2D interference to CNs. However, the interference from CNs to D2D systems is out of consideration. Yu proposed a power optimization method [12]. This method balances the interference between D2D systems and CNs. However, it needs the cellular users to reduce their power for the reliable communication of D2D systems, which lowers the performance of cellular communication. Min proposed an interference retransmission and cancellation method [13]. This method is superior to existing solutions. However, due to the base station (BS) being involved in the decoding process, the property of direct communication between users, which is the biggest advantage of D2D, disappears. Also, it should be noticed that all the aforementioned researches are implemented with help of the BS, which increases its load to some extent. Consequently, a new method which could improve the reliability of D2D without help of the BS is required.

Therefore, we start from another perspective differing from the aspect of interference suppression mechanism, and focus on the relay-aided D2D communication strategy motivated by [14]. In [14], it demonstrates that if a relay user is located between the secondary source and destination, it could lower the outage probability of secondary users in cognitive radio (CR) systems [15-16]. Although D2D users play a similar role with the secondary users of CR systems, they are different in resource usage manner, which is the major difference between D2D and CR systems [7]. Thus, it is inappropriate to directly apply the method in [14] to D2D systems underlaying CNs.

In this paper, we propose a novel D2D communication model, i.e. DF-D2D, which combines D2D users with an aided relay user using the Decode-and-Forward (DF) [17] strategy, so as to improve the reliability of D2D. In order to evaluate its performance, we firstly analyze the outage probability of DF-D2D, and obtain its exact expressions. Secondly, we compare the outage probability of DF-D2D with that of D2D, and then based on the distances between different DF-D2D users, a threshold in which the reliability of DF-D2D is better than that of D2D is obtained. Finally, analysis results are justified by simulations. The innovations of this paper are twofold: (1) a new D2D communication model is proposed; (2) the threshold which ensures the reliability of DF-D2D being superior to that of D2D is presented.

II. SYSTEM MODEL

We consider a single cell scenario which is illustrated in Fig. 1. There are N cellular users and three DF-D2D users under the control of the BS, where UE1, UE2 and UE3 are the source, the relay and the destination user, respectively.

We assume that the BS is equipped with multiple antennas, each user is equipped with a single antenna, and the BS knows all the channel state information (CSIs) of links that are connected to it. Hence, the downlink interference to DF-D2D users can be efficiently managed by the BS using the transmit beamforming technique [18]. In addition, exploiting the power control mechanism [11], the

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downlink interference to cellular users and the uplink interference to the BS from DF-D2D users are both able to be controlled. Based on above assumptions, we only focus on the uplink interference to DF-D2D users from cellular users.

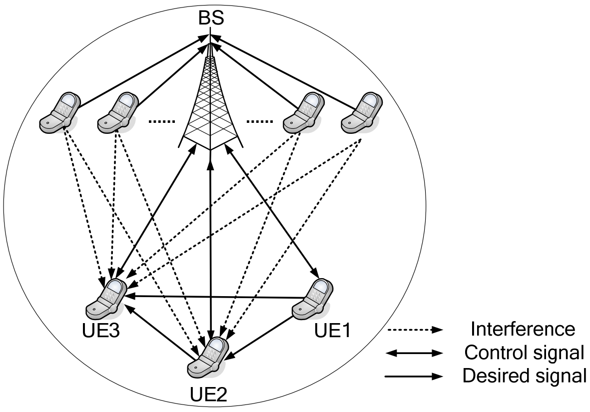

Figure 1. The system model of DF-D2D communication underlaying cellular networks

In this paper, all users are assumed to undergo Rayleigh flat fading. Therefore, the channel coefficient between UE i and UE j can be expressed as

$$h_{ij} = C_{ij}\sqrt{(d_{ij})^{-\alpha}}\left(i, j = 1,2,3\right) \quad (1)$$

where C_{ij} is an independent zero-mean circular symmetric complex Gaussian variable with unit variance, i.e. $C_{ij} \sim \mathcal{CN}(0,1)$. d_{ij} is the distance between UE i and UE j, and α is the path loss exponent.

Because DF-D2D communication is aided by a relay user using the DF strategy, so according the property of DF [17], DF-D2D proceeds at two time slots.

In the first time slot, UE1 broadcasts signal $\sqrt{P_1}s_1$ to UE2 and UE3. The received signals at UE2 and UE3 are

$$y_{\text{UE2}}^{(1)} = C_{12}\sqrt{(d_{12})^{-\alpha}P_1}s_1 + n_1 \quad (2)$$

$$y_{\text{UE3}}^{(1)} = C_{13}\sqrt{(d_{13})^{-\alpha}P_1}s_1 + n_2 \quad (3)$$

where the index within the round parentheses is the time index. P_1 is the transmit power of UE1, and $E\left(\left|s_1\right|^2\right) = 1$. n_1 and n_2 both denote the additive noise plus other interferences, which are i.i.d. zero-mean circular symmetric complex Gaussian variables with variance N_0.

In the second time slot, UE2 firstly decodes its received signal in the first time slot, and then transmits the re-encoded signal $\sqrt{P_2}\hat{s}_1$ to UE3. The received signal at UE3 is

$$y_{\text{UE3}}^{(2)} = C_{23}\sqrt{(d_{23})^{-\alpha}P_2}\hat{s}_1 + n_3 \quad (4)$$

where P_2 is the transmit power of UE2 and $E\left(\left|\hat{s}_1\right|^2\right) = 1$. n_3 denotes the additive noise plus other interferences, which is also an independent zero-mean circular symmetric complex Gaussian variables with variance N_0.

III. Analysis of The Outage Probability

In this section, we arrive at the outage probability of DF-D2D communication underlaying the cellular network, and through the comparison of outage probabilities between DF-D2D and D2D, a threshold in which the reliability of DF-D2D is better than that of D2D is obtained based on the distance between different DF-D2D users.

A. The Outage Probability of DF-D2D

When the channel conditions are poor, there will be mistakes in the decoding process of DF strategy related system [17]. Applying above results to the DF-D2D system, the message transmitted from UE1 can not be reliably decoded by UE2 in this case, and hence DF-D2D system would be interrupted.

In contrast, when the channel conditions are well, there will be no mistakes in the decoding process of DF strategy related system [17], therefore, UE2 can decode the message from UE1 accurately right now, i.e. $\hat{s}_1 = s_1$. In this case, the outage probability of DF-D2D will depend on the transmission capacity of the channel between UE1 and UE3 as well as the channel capacity between UE2 and UE3.

Thus, if the channel conditions are poor, the outage probability of DF-D2D is

$$\begin{aligned} P_{out,poor} &= \Pr\left[I_{poor} < R\right] = \Pr\left[\frac{1}{2}\log_2\left(1+\gamma_{\text{UE2}}\right) < R\right] \\ &= \Pr\left[\gamma_{\text{UE2}} < \gamma_{th}\right] \end{aligned} \quad (5)$$

where I_{poor} is the maximum average mutual information between UE1 and UE2, γ_{UE2} is the received signal-to-interference plus noise-ratio (SINR) at UE2, R is the spectral efficiency and the predetermined protection SINR γ_{th} is equal to $2^{2R} - 1$.

Accordingly, if the channel conditions are well, the outage probability of DF-D2D is

$$\begin{aligned} P_{out,well} &= \Pr\left[I_{well} < R\right] = \Pr\left[\frac{1}{2}\log_2\left(1+\gamma_{\text{UE3}}\right) < R\right] \\ &= \Pr\left[\gamma_{\text{UE3}} < \gamma_{th}\right] \end{aligned} \quad (6)$$

where I_{well} is the maximum average mutual information between input and output, and γ_{UE3} is the received SINR at UE3.

Combining with the above two channel conditions, the general outage probability of DF-D2D is

$$P_{out} = P_{out,poor} + (1 - P_{out,poor})P_{out,well} \quad (7)$$

With (5) and (6), (7) can be written as

$$\begin{aligned} P_{out} &= \Pr\left[\gamma_{\text{UE2}} < \gamma_{th}\right] + \left[\left(1 - \Pr\left[\gamma_{\text{UE2}} < \gamma_{th}\right]\right)\right. \\ &\left.\times \Pr\left[\gamma_{\text{UE3}} < \gamma_{th}\right]\right] \end{aligned} \quad (8)$$

In (8), $\Pr[\gamma < \gamma_{th}]$ is equal to $\int_0^{\gamma_{th}} f_\gamma(\gamma)d\gamma$, which is further equivalent to $F_\gamma(\gamma_{th})$. $f_\gamma(\gamma)$ and $F_\gamma(\gamma)$ mean the probability density function (PDF) and the cumulative density function (CDF) of γ, respectively.

Clearly, in order to acquire the exact expression of the outage probability, we should firstly obtain the PDFs of γ_{UE2} and γ_{UE3}, then arrive at the CDFs of γ_{UE2} and γ_{UE3} through integration, and finally achieve the desired result.

From (2), (3) and (4), the values of γ_{UE2} and γ_{UE3} are expressed as

$$\gamma_{\mathrm{UE2}} = \frac{|C_{12}|^2 (d_{12})^{-\alpha} P_1}{N_0} = |C_{12}|^2 (d_{12})^{-\alpha} L_1 \tag{9}$$

$$\begin{aligned}\gamma_{\mathrm{UE3}} &= \frac{|C_{13}|^2 (d_{13})^{-\alpha} P_1 + |C_{23}|^2 (d_{23})^{-\alpha} P_2}{N_0} \\ &= |C_{13}|^2 (d_{13})^{-\alpha} L_1 + |C_{23}|^2 (d_{23})^{-\alpha} L_2\end{aligned} \tag{10}$$

where $L_1 = \frac{P_1}{N_0}$ and $L_2 = \frac{P_2}{N_0}$ mean the transmit SINR at UE1 and UE2, respectively.

As C_{ij} ~$\mathcal{CN}(0,1)$, $f_{\gamma_{\mathrm{UE2}}}(\gamma)$ and $f_{\gamma_{\mathrm{UE3}}}(\gamma)$ can be obtained with the help of (9) and (10) [19]:

$$f_{\gamma_{\mathrm{UE2}}}(\gamma) = \frac{(d_{12})^{\alpha}}{2L_1} \exp\left(-\frac{(d_{12})^{\alpha}}{2L_1}\gamma\right) U(\gamma) \tag{11}$$

$$\begin{aligned}f_{\gamma_{\mathrm{UE3}}}(\gamma) &= \left[\exp\left(-\frac{(d_{13})^{\alpha}}{2L_1}\gamma\right) - \exp\left(-\frac{(d_{23})^{\alpha}}{2L_2}\gamma\right)\right] \\ &\times \frac{(d_{13}d_{23})^{\alpha}}{2L_1(d_{23})^{\alpha} - 2L_2(d_{13})^{\alpha}} U(\gamma)\end{aligned} \tag{12}$$

where $U(\gamma)$ is the unit-step function.

Through simple integration, $F_{\gamma_{\mathrm{UE2}}}(\gamma)$ and $F_{\gamma_{\mathrm{UE3}}}(\gamma)$ are transformed to:

$$F_{\gamma_{\mathrm{UE2}}}(\gamma) = 1 - \exp\left(-\frac{(d_{12})^{\alpha}}{2L_1}\gamma\right) \tag{13}$$

$$\begin{aligned}F_{\gamma_{\mathrm{UE3}}}(\gamma) &= 1 + \frac{L_1(d_{23})^{\alpha}}{L_2(d_{13})^{\alpha} - L_1(d_{23})^{\alpha}} \exp\left(-\frac{(d_{13})^{\alpha}}{2L_1}\gamma\right) \\ &- \frac{L_2(d_{13})^{\alpha}}{L_2(d_{13})^{\alpha} - L_1(d_{23})^{\alpha}} \exp\left(-\frac{(d_{23})^{\alpha}}{2L_2}\gamma\right)\end{aligned} \tag{14}$$

By substituting $\gamma = \gamma_{\mathrm{th}}$ into (13) and (14), and with the result of (8), the outage probability of DF-D2D is obtained:

$$\begin{aligned}P_{out} &= 1 + \left[L_1(d_{23})^{\alpha} \exp\left(-\frac{(d_{13})^{\alpha}}{2L_1}\gamma_{th}\right)\right. \\ &\left. - L_2(d_{13})^{\alpha} \exp\left(-\frac{(d_{23})^{\alpha}}{2L_2}\gamma_{th}\right)\right] \times \frac{\exp\left(-\frac{(d_{12})^{\alpha}}{2L_1}\gamma_{th}\right)}{L_2(d_{13})^{\alpha} - L_1(d_{23})^{\alpha}}\end{aligned} \tag{15}$$

B. Comparison of Outage Probabilities

In the previous subsection, the outage probability of DF-D2D has already been shown. In this subsection, we will make a comparison of outage probabilities between DF-D2D and D2D, and subsequently produce a threshold of the distance between different DF-D2D users in which the reliability of DF-D2D is better than that of D2D.

To be noticed, the significant differences between DF-D2D and D2D are the following aspects: (1) there exists an additional aided relay user in the former, whereas there are only a source and a destination user in the latter; (2) the former proceeds at two time slots, but the latter proceeds at only one time slot. In order to facilitate comparison, here we show the system model of D2D in Fig. 2 and use the same user number as that in Fig. 1.

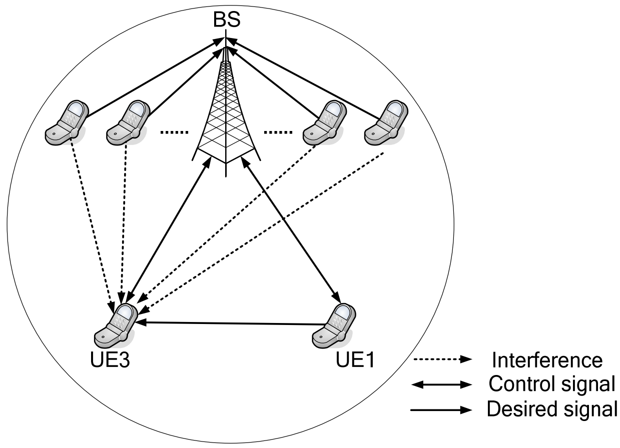

Figure 2. The system model of D2D communication underlaying cellular networks

Similar to the derivation in the previous subsection, we could arrive at the outage probability of D2D:

$$P_{out,D2D} = 1 - \exp\left(-\frac{(d_{13})^{\alpha}}{2L_1}\gamma_{\mathrm{th}}'\right) \tag{16}$$

where $\gamma_{\mathrm{th}}' = 2^R - 1$.

Comparing the outage probability of DF-D2D with the one of D2D is equivalent to comparing P_{out} with $P_{out,D2D}$. If we want the former to be lower than the latter, then the relational expression of (15) and (16) could be written as

$$\begin{aligned}&\frac{\exp\left(-\frac{(d_{12})^{\alpha}}{2L_1}\gamma_{th}\right)}{L_2(d_{13})^{\alpha} - L_1(kd_{13})^{\alpha}} \times \left[L_2(d_{13})^{\alpha} \exp\left(-\frac{(kd_{13})^{\alpha}}{2L_2}\gamma_{th}\right)\right. \\ &\left. - L_1(kd_{13})^{\alpha} \exp\left(-\frac{(d_{13})^{\alpha}}{2L_1}\gamma_{th}\right)\right] > \exp\left(-\frac{(d_{13})^{\alpha}}{2L_1}\gamma_{th}'\right)\end{aligned} \tag{17}$$

where $d_{23} = kd_{13}\,(k \in \mathbb{R})$ represents the relationship between d_{13} and d_{23}.

Through derivation, the threshold in which the reliability of DF-D2D is better than that of D2D, based on the distance between the source and relay user, is shown:

$$d_{12} < \left\{ \frac{(d_{13})^{\alpha} \gamma_{th}'}{\gamma_{th}} + \frac{2L_1}{\gamma_{th}} \times \left[\ln\left(L_2 \exp\left(-\frac{(kd_{13})^{\alpha}}{2L_2} \gamma_{th} \right) - k^{\alpha} L_1 \exp\left(-\frac{(d_{13})^{\alpha}}{2L_1} \gamma_{th} \right) \right) - \ln\left(L_2 - k^{\alpha} L_1 \right) \right] \right\}^{\frac{1}{\alpha}} \tag{18}$$

IV. Numerical Results

In this section, numerical results and Monte Carlo simulations are shown to verify our analysis. We normalize the radius of the cellular cell as 1, the distance between UE1 and UE3 as 1, and the distance between UE2 and UE3 as 0.5. The path-loss exponent α is setting as 3 representing the urban macro cell [20]. Key simulation parameters are summarized in Table I.

TABLE I. KEY SIMULATION PARAMETERS

Simulation Parameters	Value
Normalized radius of the cell	1
Normalized distance between UE1 and UE3	1
Normalized distance between UE2 and UE3	0.5
Path-loss exponent	3

In Fig. 3 and Fig. 4, the outage probability of DF-D2D is analyzed according to the location of the relay user.

Fig. 3 shows the outage probability versus the predetermined protection SINR. In this figure, $P_1 = P_2$, $P_1/N_0 = 10$ dB, and d_{12} is setting as different values according to the threshold derived in (18), where $\max(d_{12})$ appearing in the figure represents the maximum threshold value. From this figure, we can see that DF-D2D could achieve better outage performance than D2D within the threshold. Besides, the outage performance of DF-D2D becomes better along with the decrease of the distance between UE1 and UE2.

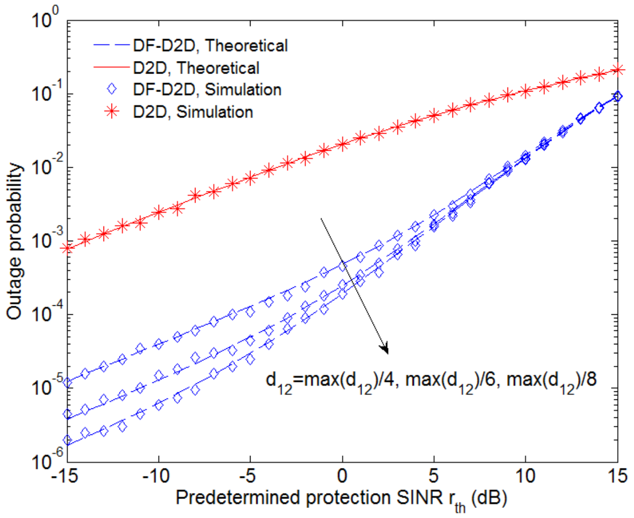

Figure 3. The outage probability of DF-D2D according to the location of the relay user (versus the predetermined protection SINR)

Fig. 4 shows the outage probability versus the transmit SINR at UE1. In this figure, $R = 0.5$, $P_1 = P_2$, and d_{12} is changed within the derived threshold. From this figure, we can see that DF-D2D is superior in the outage performance compared with D2D, and the outage probability of DF-D2D becomes lower as the distance between UE1 and UE2 decreases, which is also presented in Fig. 3.

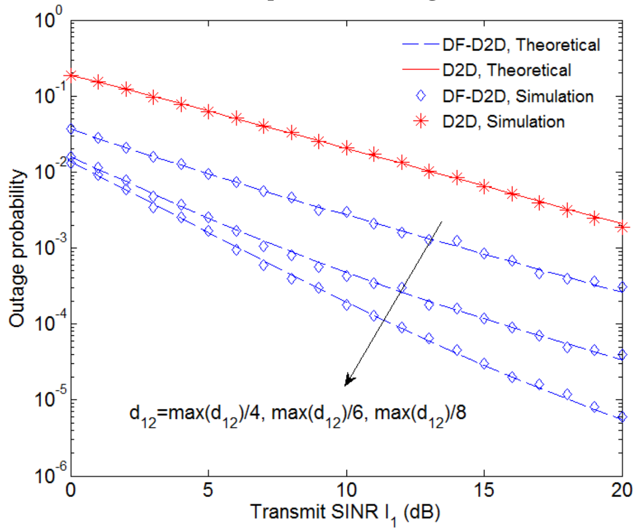

Figure 4. The outage probability of DF-D2D according to the location of the relay user (versus the transmit SINR at UE1)

In Fig. 5 and Fig. 6, the outage probability of DF-D2D is analyzed according to the transmit power of the relay user.

Fig. 5 shows the outage probability versus the predetermined protection SINR. In this figure, $d_{12} = \max(d_{12})/4$, $P_1/N_0 = 10$ dB, and the transmit power ratio between UE2 and UE1 (i.e., P_2/P_1) is changed. From the results shown in this figure, we can see that the outage probability of DF-D2D is lower than the one of D2D within the derived threshold, and better outage performance of DF-D2D could be achieved by increasing the transmit power of UE2.

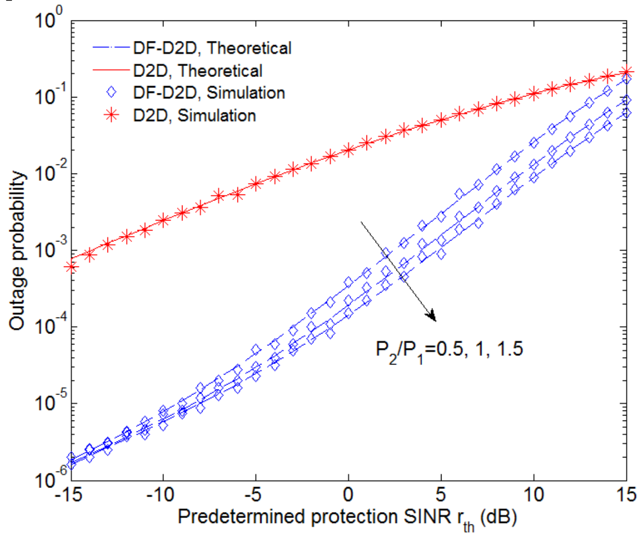

Figure 5. The outage probability of DF-D2D according to the transmit power of the relay user (versus the predetermined protection SINR)

Fig. 6 shows the outage probability versus the transmit SINR at UE1. In this figure, $d_{12} = \max(d_{12})/4$, $R = 0.5$, and P_2/P_1 is changed. Similarly with the result shown in Fig. 5, better outage performance of DF-D2D could be achieved as the transmit power of UE2 increases.

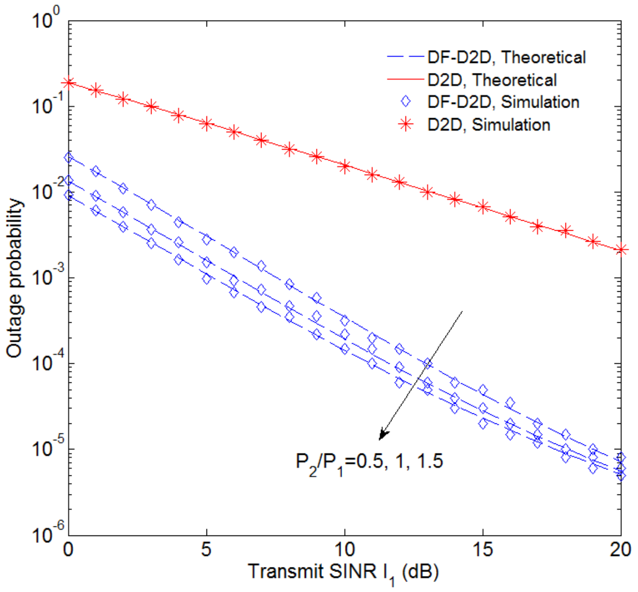

Figure 6. The outage probability of DF-D2D according to the transmit power of the relay user (versus the transmit SINR at UE1)

As we know, DF strategy is also widely used in wireless relaying system with no direct links between the source and destination user [21]. In order to test the influence of this direct link on the outage performance of DF-D2D, we compare the outage probabilities of DF-D2D with a direct link and without a direct link. For simplicity, the latter adopts the former where three users lie on a line.

Through simple derivation, the outage probability of DF-D2D without a direct link is obtained as

$$P_{out,no-direct} = 1 - \exp\left(-\frac{(d_{12})^{\alpha}}{2L_1}\gamma_{\text{th}} - \frac{(d_{23})^{\alpha}}{2L_2}\gamma_{\text{th}} \right) \quad (19)$$

and the comparisons are shown in Fig. 7 to Fig. 10.

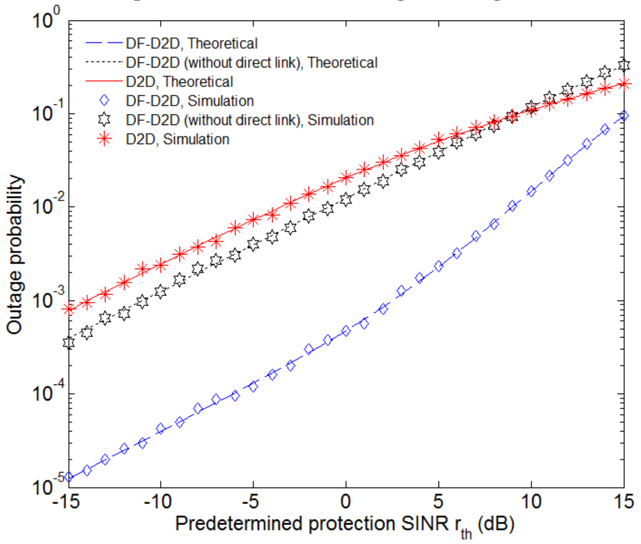

Figure 7. The comparison between outage probabilities of DF-D2D with and without a direct link according to the location of the relay user (versus the predetermined protection SINR)

In Fig. 7 and Fig. 8, the outage probabilities are analyzed according to the location of the relay user. For DF-D2D with a direct link, d_{12} is changed within the derived threshold and equal to $\max(d_{12})/4$, whereas for DF-D2D without a direct link, d_{12} is fixed and equal to 0.5. In these two figures, expect for d_{12}, we use the same setting parameters as that in Fig. 3 and Fig. 4, respectively. From the results presented in both figures, it is clearly that DF-D2D with a direct link could achieve better outage performance within the threshold, compared with DF-D2D without a direct link, whenever versus the predetermined protection SINR or the transmit SINR at UE1.

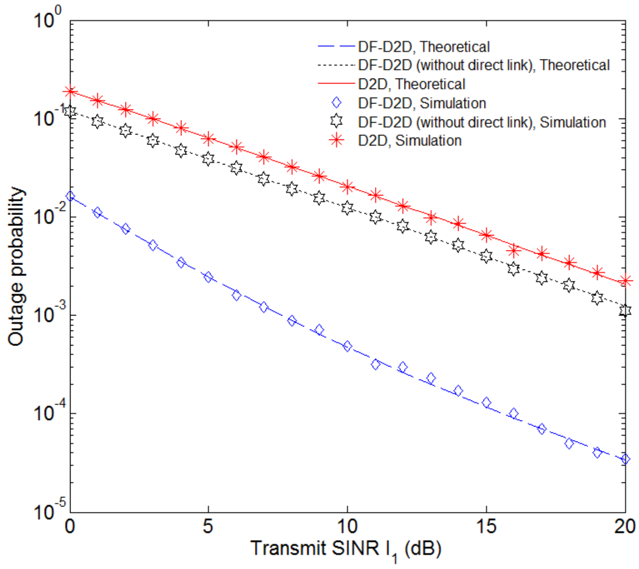

Figure 8. The comparison between outage probabilities of DF-D2D with and without a direct link according to the location of the relay user (versus the transmit SINR at UE1)

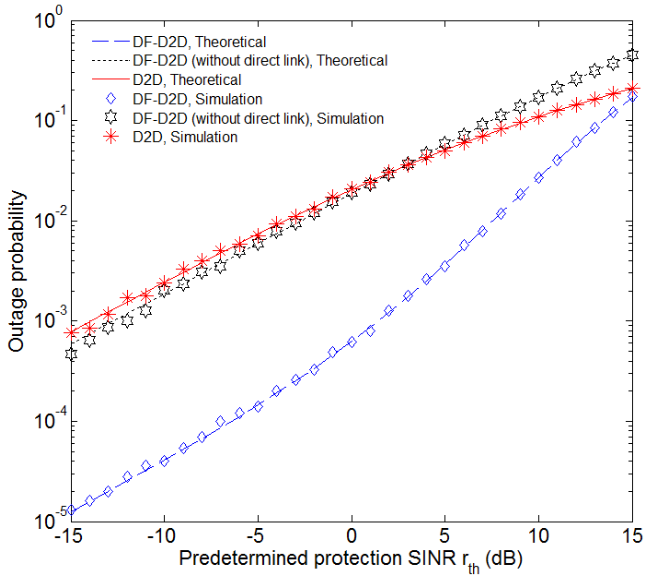

Figure 9. The comparison between outage probabilities of DF-D2D with and without a direct link according to the transmit power of the relay user (versus the predetermined protection SINR)

In Fig. 9 and Fig. 10, the outage probabilities are analyzed according to the transmit power of the relay user. In these two figures, $d_{12} = \max(d_{12})/4$ for DF-D2D with a direct link, whereas $d_{12} = 0.5$ for DF-D2D without a direct link. $P_2/P_1 = 0.5$, and the other setting parameters are the same as that in Fig. 5 and Fig. 6, respectively. From the results shown in both figures, we can see that the outage performance of DF-D2D without a direct link is still worse than that of DF-D2D with a direct link.

Combined with the results in Fig. 3 to Fig. 10, it can be concluded that DF-D2D could achieve better outage performance than conventional D2D, and the direct link between the source and destination user is beneficial to the outage performance of DF-D2D.

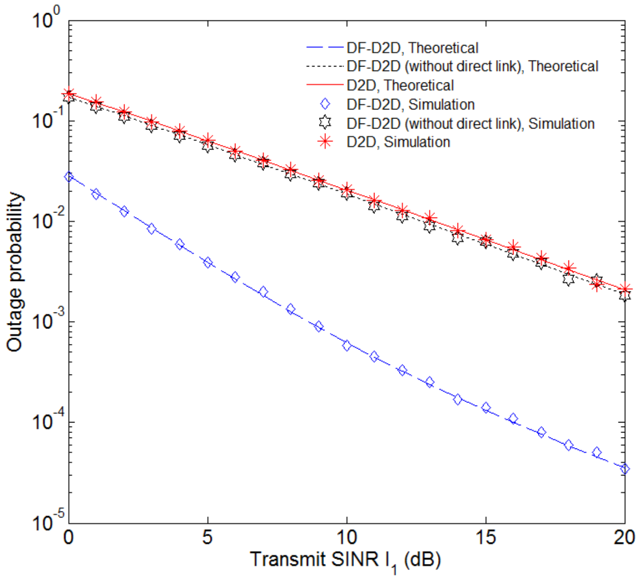

Figure 10. The comparison between outage probabilities of DF-D2D with and without a direct link according to the transmit power of the relay user (versus the transmit SINR at UE1)

V. Conclusion

In this paper, we propose the new DF-D2D communication model underlaying the cellular network. Comparing with the conventional D2D communication model, an aided relay user using the DF strategy is introduced in DF-D2D. In addition, we derive the exact outage probability expression of DF-D2D and obtain a distance threshold in which the reliability of DF-D2D is better than that of D2D. With the numerical results and Monte Carlo simulations, it shows that our proposed scheme could provide increased reliability than the conventional one in terms of the outage performance if the location of the relay user changes within the threshold, as well as the transmit power of the relay user increases.

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